Isospin Asymmetry in Nuclei, Neutron Stars, and Heavy-Ion Collisions

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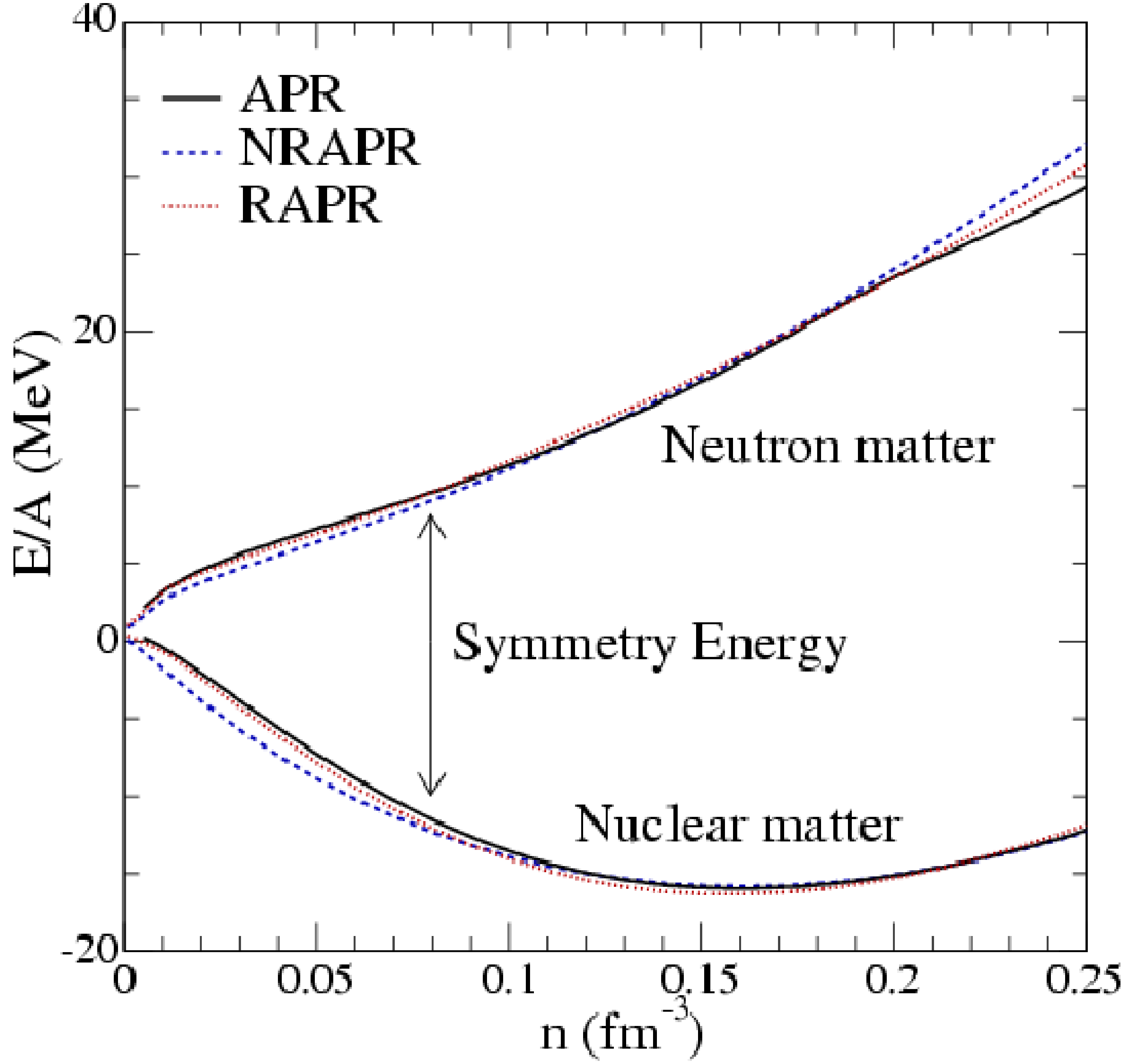
Outline

- Symmetry Energy
- Equation of State of Dense Matter
  - What do we know?
- Connection to heavy ion collisions
- Correlations
  - How correlations are useful
  - Three particular correlations
- What can we learn?

The Nuclear (A)symmetry Energy

- The symmetry energy is the size of the energy cost in QCD of creating an asymmetry between the number of neutrons and protons
- Note that the pressure (at zero T) is related to the derivative of the energy per baryon (E/A)
- Of concern is the magnitude of the symmetry energy and its density dependence



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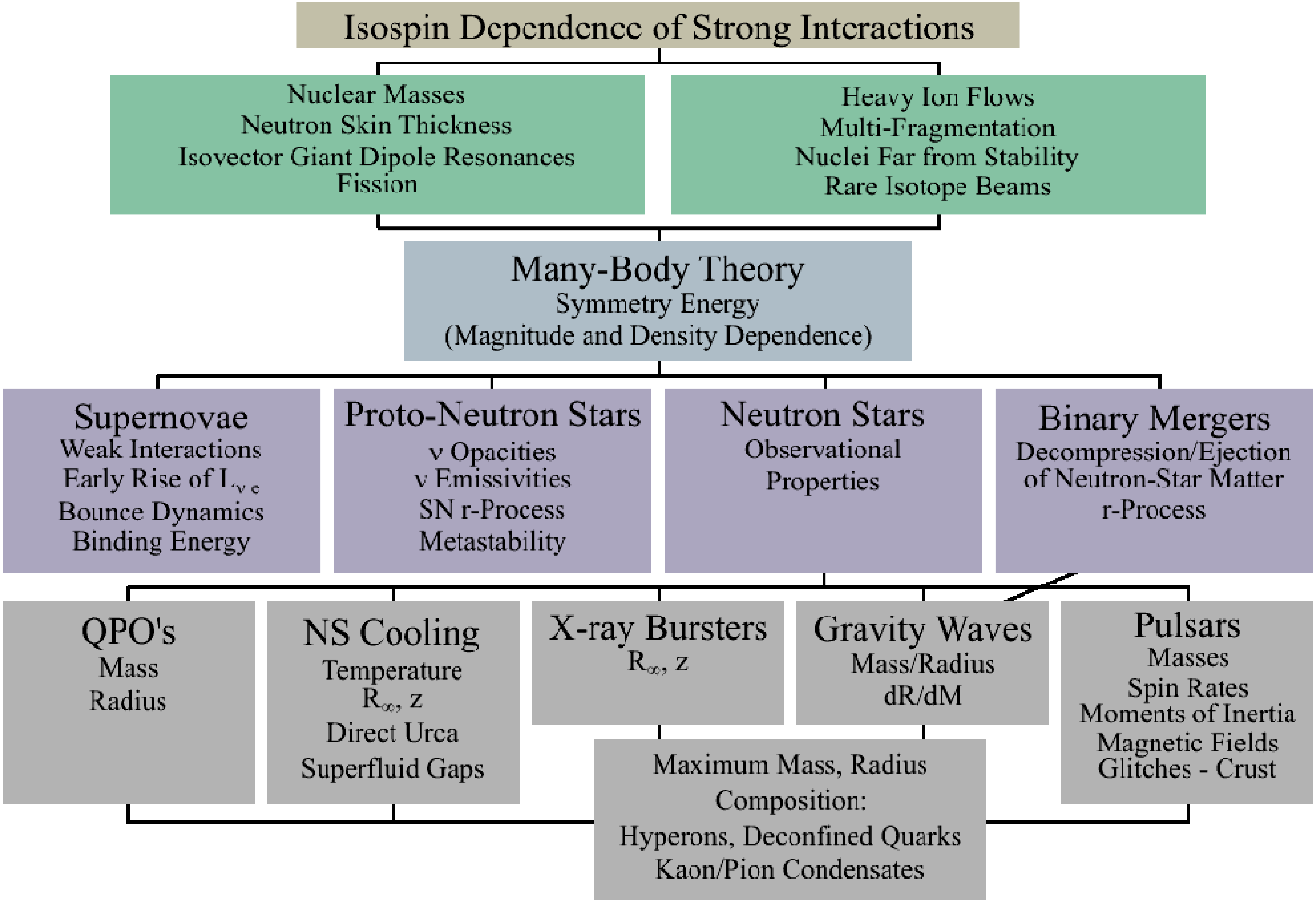
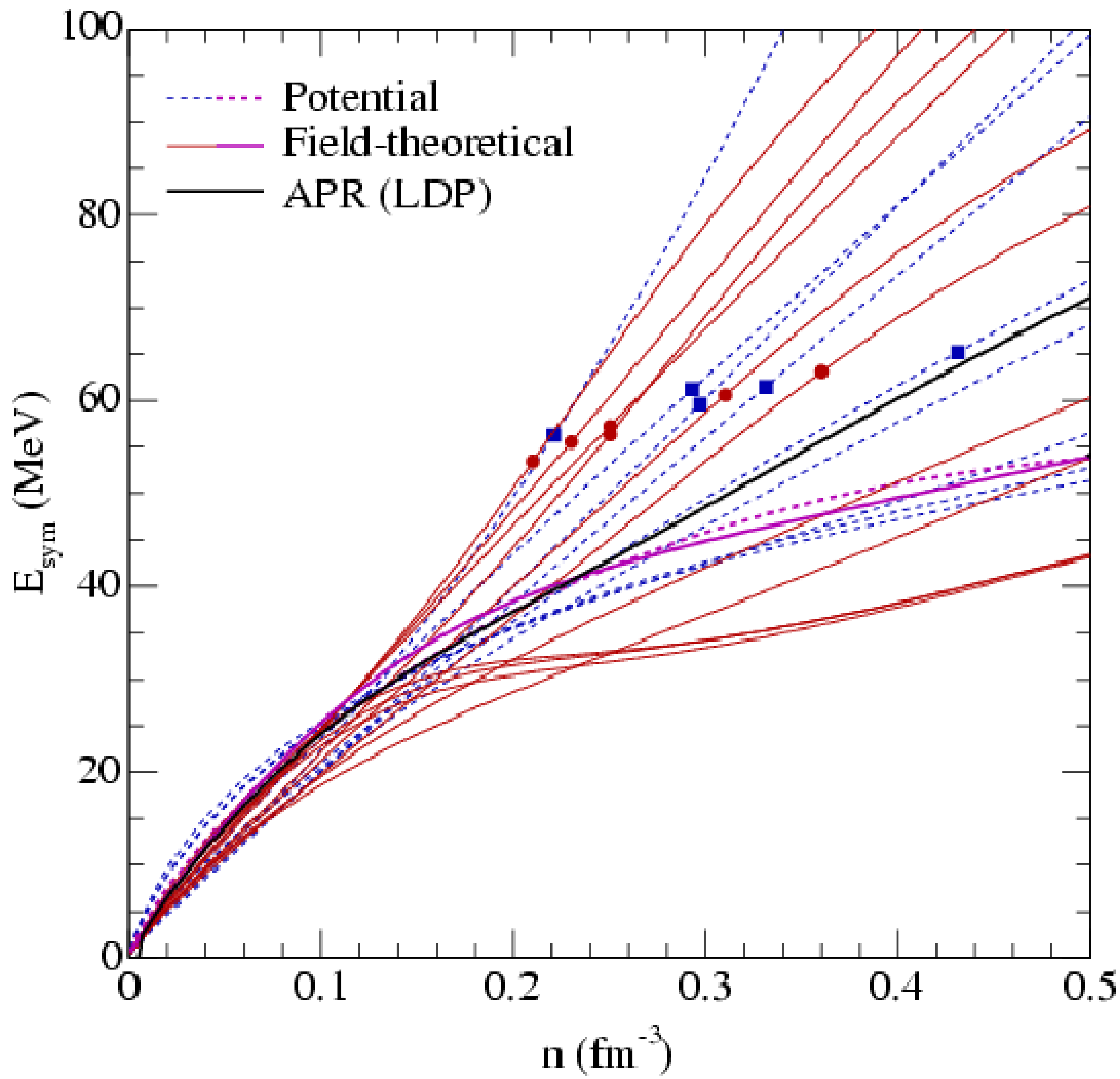
The Influence of the Nuclear Symmetry Energy



The Nuclear Symmetry Energy

- There is considerable variation among models, both relativistic and non-relativistic
- Relativistic models = Extensions of the Walecka model to include higher order interactions between the isoscalar and isovector mesons
- Non-relativistic models = Skyrme Hamiltonian
- APR = Akmal, et. al. - Ab-initio Monte Carlo calculations of nuclear and neutron matter



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What do we know about the EOS?

- Properties of saturated nuclear matter: binding energy, saturation density, compressibility, effective mass, symmetry energy (25-35 MeV)
- Nuclear structure: nuclear binding energies and charge density distributions
  - Binding energies and charge radii of doubly-magic nuclei (^{208}Pb, ^{90}Zr, ^{40}Ca) in the Hartree and Hartree-Fock approximations.
- Stability
  - Restrictions on the Landau parameters
  - Pressure should increase with density
  - Chemical potential should increase with concentration
- Neutron stars: Must be able to support a 1.44 solar mass neutron star (This may change soon!)
- These quantities are *easy* to calculate for a given EOS.

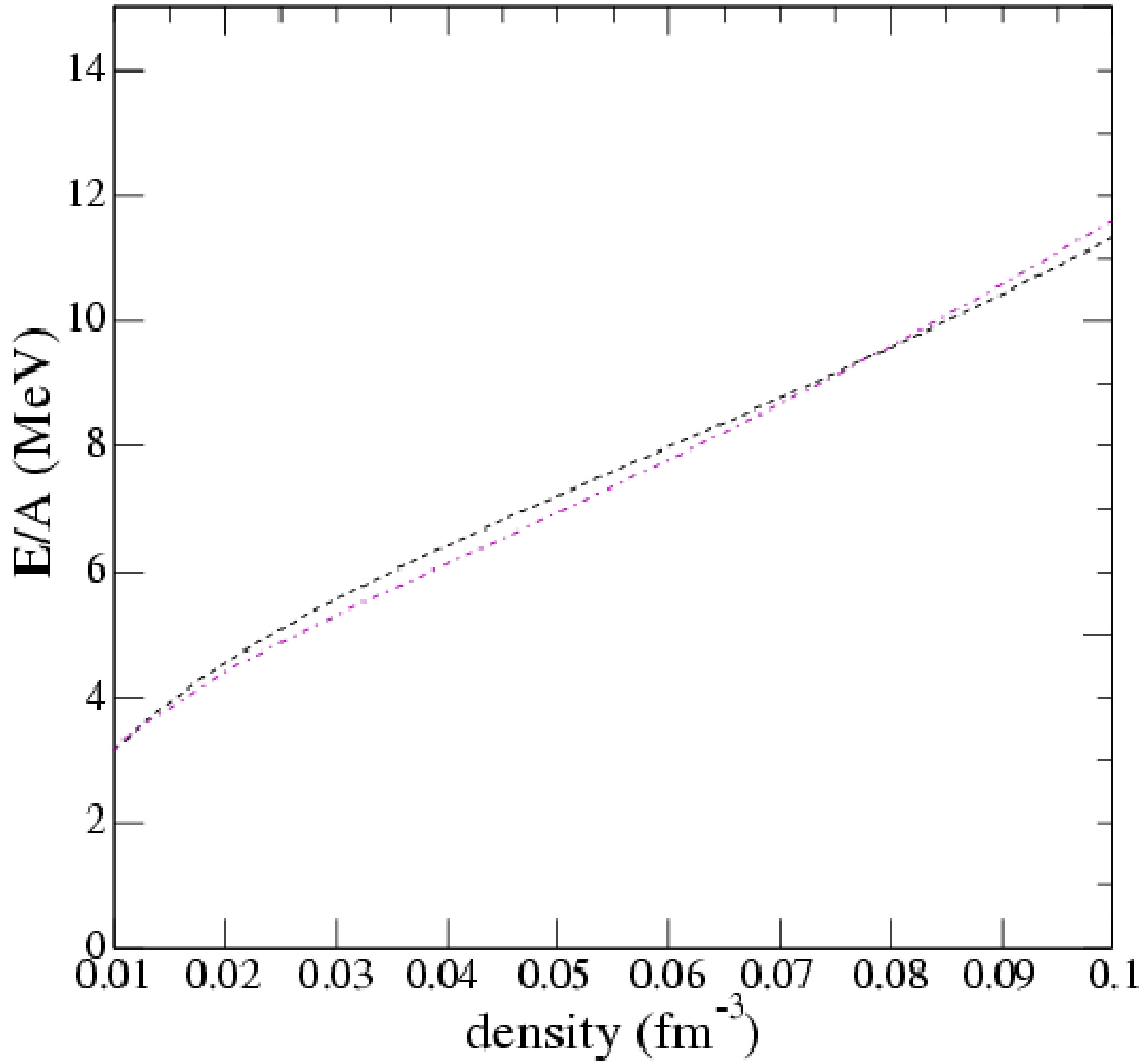
Fitting APR

- Original calculations based on exact methods accesible for A<16
- Fit the APR results to both a relativistic and non-relativistic model
- Now we can calculate large A nuclei!

Nucleus	Property	Experiment	Potential	Field-theoretical
^{208}Pb	Charge radius (fm)	5.50	5.41	5.41
	Binding energy (MeV)	7.87	7.87	7.77
	Skin thickness (fm)	0.12 ± 0.05, 0.20 ± 0.04	0.19	0.20
^{90}Zr	Charge radius (fm)	4.27	4.18	4.17
	Binding energy (MeV)	8.71	8.88	8.65
	Skin thickness (fm)	0.09 ± 0.07	0.075	0.093
^{40}Ca	Charge radius (fm)	3.48	3.40	3.34
	Binding energy (MeV)	8.45	8.89	8.61
	Skin thickness (fm)	-0.06 ± 0.05, -0.05 ± 0.04	-0.044	-0.046

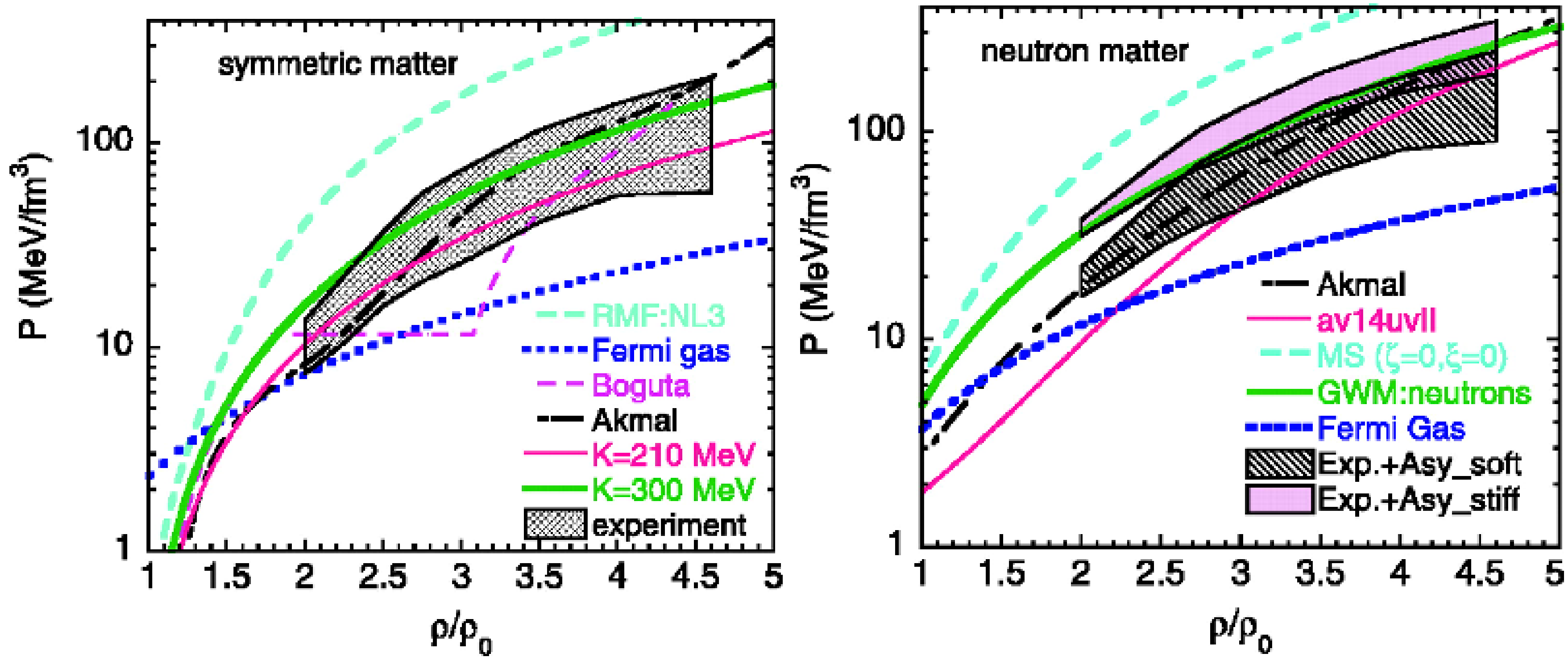
Low-density neutron matter

- Ab-initio calculations (like APR) of neutron matter predicit a fairly precise behavior of the EOS at low densities
- The energy per baryon should be about 1/2 the Fermi gas energy
- Our relativisitic fits to APR demonstrate that this is possible to express in a field-theoretical context
- This results in a clear finite-temperature generalization



Symmetry Energy and Heavy-Ion Collisions

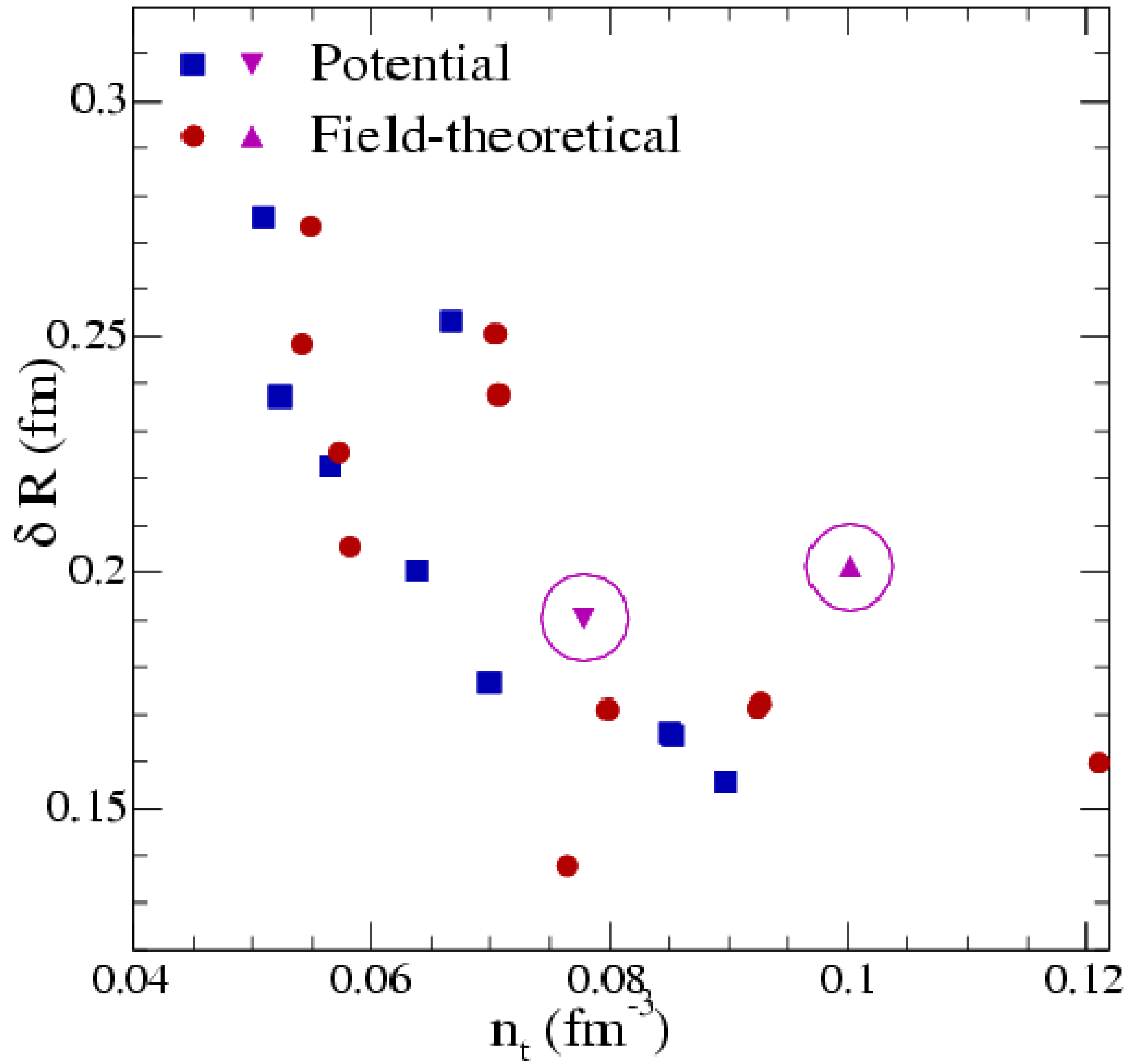
- Heavy-ion collision observables are providing constraints on the symmetry energy
- More repulsion leads to higher pressures and more out-of-the plane emission.
- Elliptic flow



Taken from Danielewicz, Lacey, and Lynch, Science 298 (2002) 1592.

Symmetry Energy and Heavy-Ion Collisions

- **Isotope separation instability** - If the symmetry energy becomes negative then it is energetically favorable for matter to separate into two phases. This has several observable implications in heavy-ion collisions. (Li 2002)
- **Multifragmentation** has been used to calculate the critical temperature of the liquid-gas phase transition (Li and Ko 1997 and Xu et. al. 2000)
- **Isoscaling** - Scaling laws in isotope yields measured in two different nuclear reactions (Tsang et. al. 2001 and Ono et. al. 2003)
- **Isospin Diffusion** (Li 2002 and 2005)



Correlations

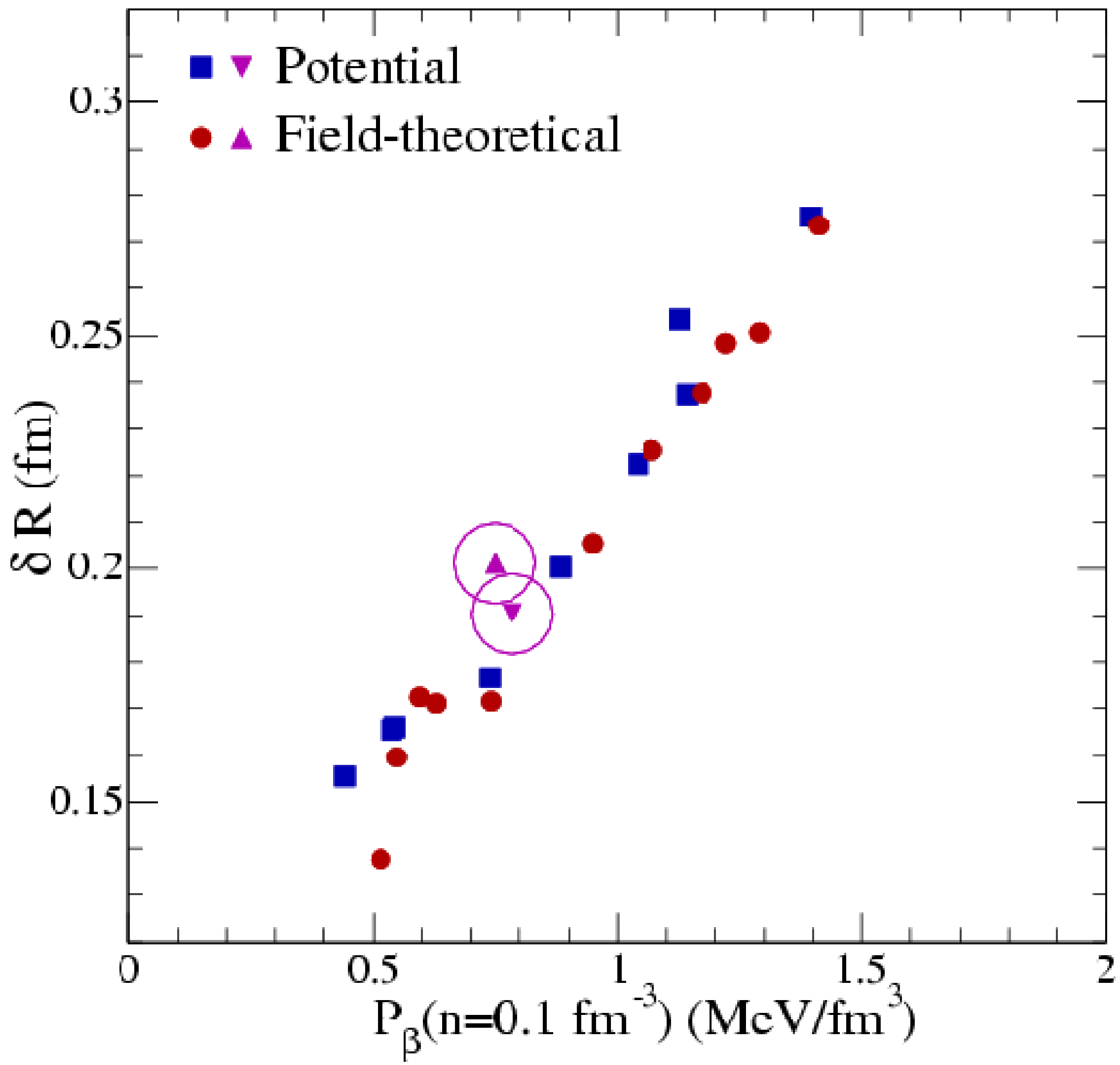
- If we have a correlation between two experimental observables - hopefully a measurement of one will offer a prediction of the other
- How accurately can we calculate these observables from an equation of state? Systematic uncertainties?
- Understand our calculations
- Calculate those observables with as many EOSs as possible... ...making sure that we restrict ourselves only to EOSs which match what we know.
- We found very few models which matched this criteria, so in some cases, we made our own.

The Skin Thickness of Lead

- The "neutron skin thickness" is the difference between the neutron and proton rms radii:
  $\sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$
- This number is tightly correlated to the pressure of neutron matter at a particular density
- The pressure of neutron matter is almost entirely determined by the symmetry energy
- The neutron skin thickness of Pb^{208} will be measured accurately at Jefferson Lab

$$\frac{\sigma_\delta}{E_{\mathrm{sym}}} \sim \int \left[\frac{E_{sym}}{E_{sym}(n)} - 1 \right] \frac{n}{[\mathcal{H} + nB]^{1/2}} dn$$

$$\delta R \sim \frac{2\delta_L}{(1-\delta_L^2)} \frac{\sigma_\delta}{E_{\mathrm{sym}}}$$



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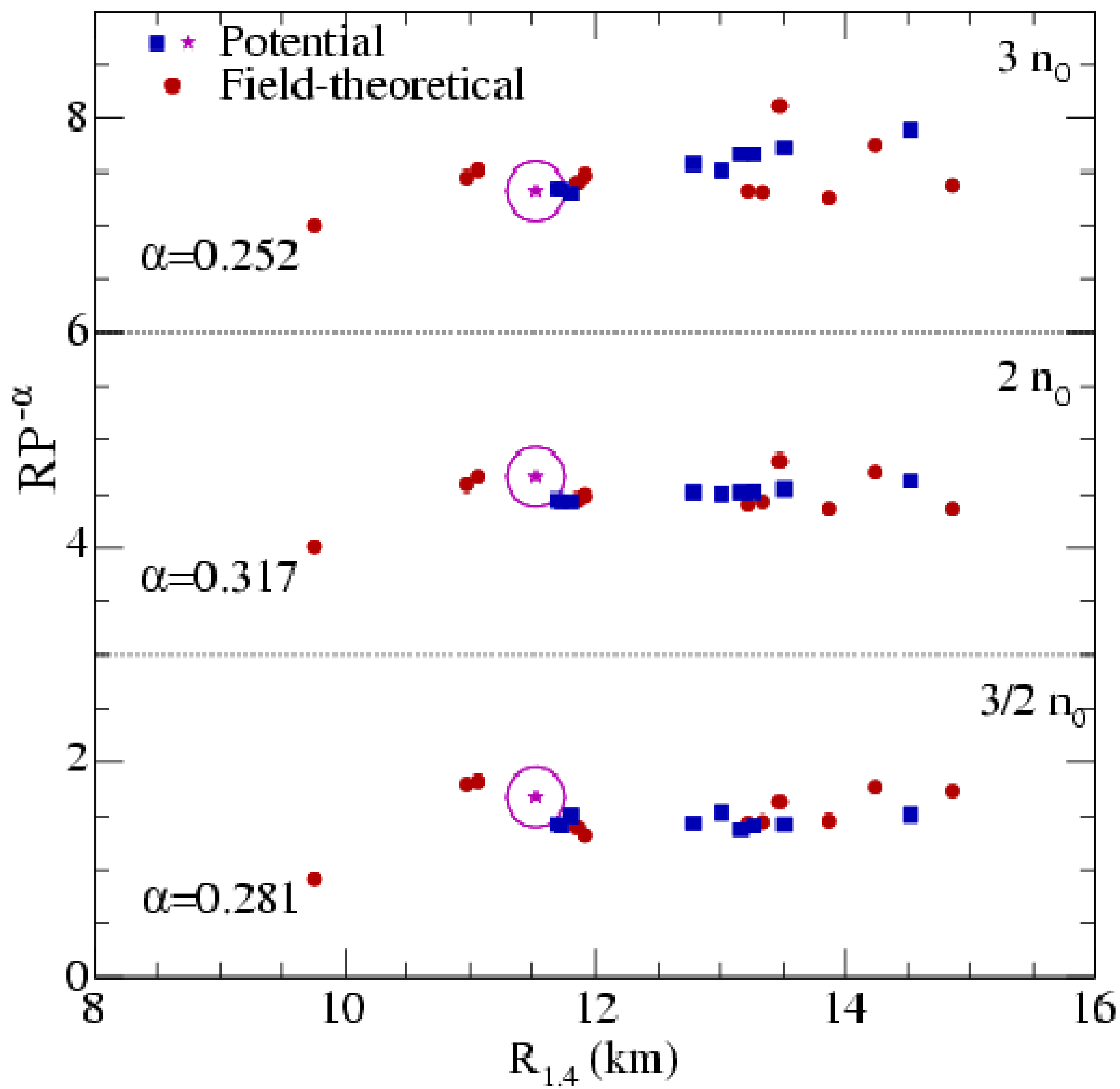
Lattimer-Prakash correlation

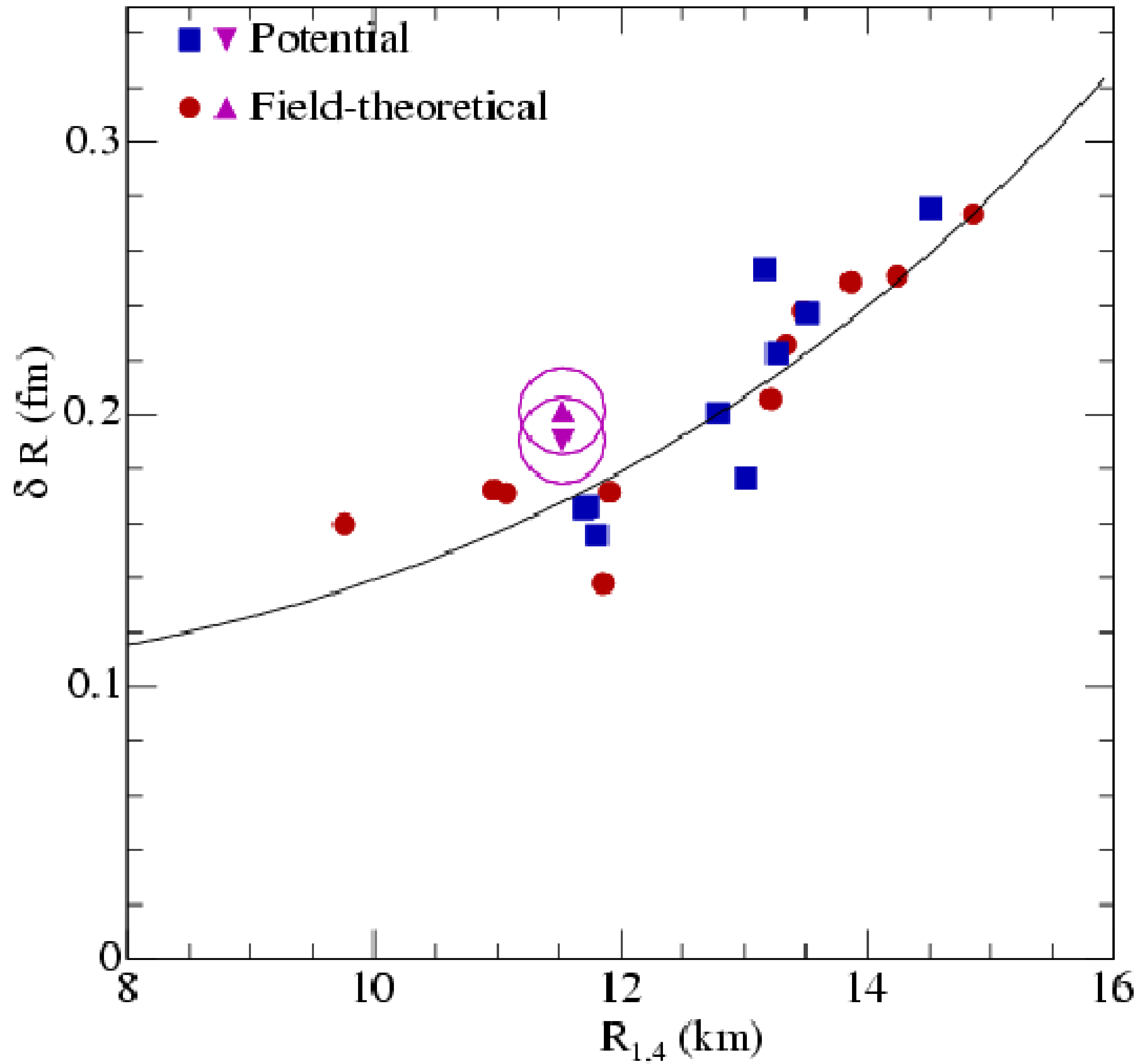
- Analytical solutions of the Tolman-Oppenheimer-Volkov equations suggest that $R \sim RP^{-\alpha}$

- So the radius is correlated with the pressure at densities somewhat larger than nuclear matter densities



Horowitz-Piekarewicz correlation

- $\delta R \Leftrightarrow P \Leftrightarrow R_{NS}$
- This emerges naturally from the two previous correlations if the pressure at the two densities are correlated
- We find that this correlation is not quite linear, but obeys a power law
- A similiar correlation for the radius of the maximum mass star



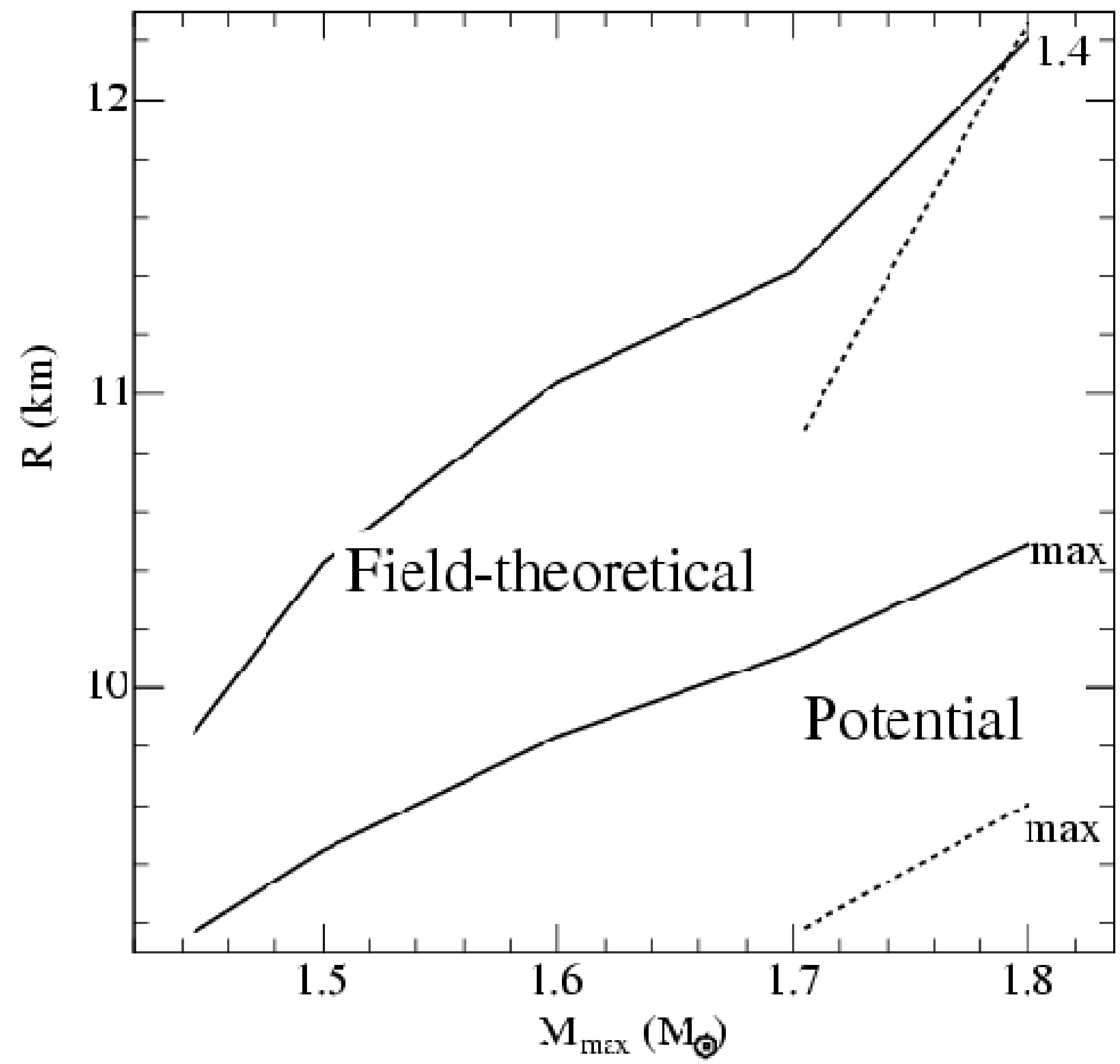
What can we learn?

Symmetry Energy	Small symmetry energy	Large symmetry energy
Neutron stars	Small neutron star radii	Large neutron star radii
	Small moment of inertia	Large moment of inertia
	Slow modified URCA cooling	Fast direct URCA cooling
	More robust r-process	Less robust r-process
Nuclear Structure	Small skin thickness in lead	Large skin thickness in lead
	Smaller surface/volume contribution	Larger surface/volume contribution
Heavy-Ion Collisions	Less isospin-asymmetric flow	More isospin-asymmetric flow
	Possible isotope separation instability	No isotope separation instability
	Large liquid-gas transition density	Small liquid-gas transition density

- A sufficiently large neutron skin thickness rules out any isotope separation instability
- A large liquid-gas transition density would rule out large neutron star radii
- Too much flow would rule out a smaller neutron skin thickness in lead

Small Neutron Star Radii

- What is the smallest radius for a neutron star which doesn't contain exotic components?
- Largest accurate mass measurements used to be 1.44 $M_\odot$
- Recent neutron star mass measurements suggest masses at least 1.9 - 2 $M_\odot$



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Summary

- Determining the symmetry energy is within our reach, but...
- ...it will likely demand information from nuclear structure, astrophysics, and heavy-ion collisions.